NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING
2019 Pacific Conference on Earthquake Engineering
TURNING HAZARD AWARENESS INTO RISK MITIGATION
4 – 6 April | SkyCity, Auckland | New Zealand

Eco-rubber seismic-isolation foundation systems: a cost-effective way to build resilience

G. Chiaro, A. Palermo, G. Granello, A. Tasalloti & C. Stratford
Dept. of Civil and Natural Resources Engineering University of Canterbury, Christchurch, New Zealand.

L.J. Banasiak
Environmental Science and Research Institute, Christchurch, New Zealand.

ABSTRACT

Seismic isolation (SI) with energy dissipation has the ability to significantly improve the seismic performance of structures. Historically, SI has been applied to buildings with special functional requirements and bridges. Nevertheless, its application to create new earthquake-resilient residential housing would be of great significance in New Zealand. In this context, this paper proposes an innovative and cost-effective SI methodology, particularly suitable for medium-density low-rise buildings, making use of a dissipative filter made of granulated tyre rubber–gravel mixtures and fibre-reinforced rubberised concrete foundation structural elements. While detailed experimental and numerical results are not available yet, in this paper a state-of-the-art literature review demonstrating the feasibility of this technology is presented and the MBIE Smart Idea project “Eco-rubber seismic isolation foundation systems” that aims at developing this technology is introduced.

1 INTRODUCTION

The current rate of waste tyres production in New Zealand is over 5 million per year (Figure 1) and is expected to grow over time with increased population and number of vehicles on the road. An estimated 70% of such waste tyres are destined for landfills, stockpiles, illegal disposal or are otherwise unaccounted for (Ministry for the Environment 2015), giving rise to piles of tyres that do not readily degrade or disintegrate. With the ever-growing volume of waste tyres, environmental concerns have urged the reuse of waste tyres through large-scale recycling engineering projects.

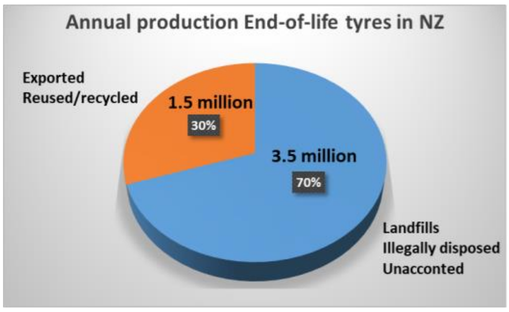

Figure 1. Production of EOL tyres in NZ

Waste tyres are a great source of environmentally-friendly and sustainable building materials that can be made affordable and ready available through technological innovations. For example, they may provide novel and effective engineering solutions to attain structures with enhanced seismic resilience (Tsang 2008, 2012). This makes them ideal materials for developing affordable, medium-density, low-rise buildings that are in high demand in New Zealand.

Based on the above-mentioned background and aimed at addressing this problem, a multi-stage comprehensive geo-environmental-structural experimental research programme is being currently carried out at the University of Canterbury to investigate sustainable options for the reuse/recycling of waste tyre in civil engineering applications. One such option is to employ waste tyre (in the form of granulated tyre rubber - GTR) mixed with gravelly soils to develop seismic-isolation foundation systems for low-rise buildings.

While this system is conceptually similar to conventional discrete elastomeric seismic isolation on rubber bearings (i.e. base-isolation), it differs in that the proposed system will be continuously distributed along the contact surface separating the building or series of multi-storey/multi-dwelling complexes from the ground. For this reason, the accelerations and consequent seismic inertial forces would be reduced at least by 40% (Tsang 2008).

Although complete experimental and numerical results are not available yet, in this paper a state-of-the-art literature review is presented to demonstrate the feasibility of this technology, and the MBIE Smart Idea project "Eco-rubber seismic isolation foundation system" that aims at developing this technology is introduced.

2 STATE-OF-THE-ART LITERATURE REVIEW

2.1 Soil-rubber mixture: dynamic geotechnical properties

In recent decades, scrap tyre derived materials (in the form of chips, crumbs, granules, and shreds) mixed with granular soil (mainly sand) have been used in civil/geotechnical applications such as light backfill material, drainage layers, slope stabilisation and landfill construction. More recently, investigation on the dynamic properties of soil-rubber mixtures exhibited interesting results that enables them to be used as seismic isolation material in foundation design. Numerical modelling conducted by Tsang et al (2012) indicated that by inclusion of a soil-rubber layer around the foundation of a low-rise building, the maximum horizontal acceleration at the roof and footing under earthquake loading could be reduced by up to 70%. Similarly, Brunet et al (2016) reported that a layer (2-3 m) of soil-rubber mixture underneath a structure could decrease peak acceleration at the base by 54%.

There are several factors influencing the dynamic response of soil-rubber mixtures such as rubber content, soil type and shape (sand, gravel, rounded, angular), rubber type (fibres, crumbs, shreds, buffing, granules), relative particle size between soil and rubber ($D_{50,s}/D_{50,r}$), confining pressure etc. These parameters have been extensively considered for mixtures of sand-rubber under monotonic and dynamic loading and the behaviour of these blends have been well determined (Senetakis et al 2012). Although rubber improved the dynamic properties of soil (mainly increasing damping ratio), there is a threshold for maximum rubber content. Beyond this threshold (~35-45% by weight), shear strength of the mixture reduces significantly due to lack of soil-soil particle interactions (Edinçliler & Cagatay 2013, Lee et al 2014, Mashiri et al 2016). Therefore, the rubber content in the matrix should be limited to some extent. Experimental research on both sand-rubber and gravel-rubber mixtures conducted by Senetakis et al (2012) revealed that by increasing rubber content in the mixture,

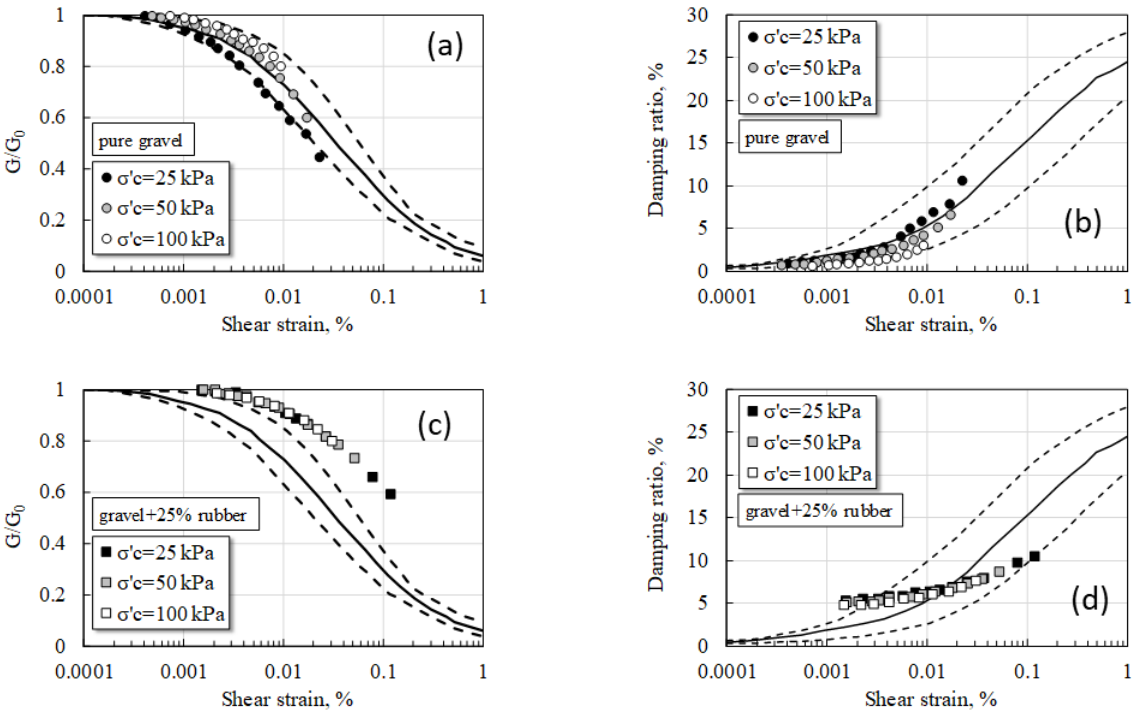

Figure 2: Effect of confining pressure and rubber content on the small-strain shear modulus and damping ratio of gravel-rubber mixtures (adopted from Senetakis et al 2012).

damping ratio increases, whereas small-strain shear modulus decreases. The effect of confining pressure and rubber content on the small-strain shear modulus decay (G/G_0) and damping ratio of gravel-rubber mixtures is illustrated in Figure 2. For better comparison, the proposed curves by Seed et al (1986) for sandy soil are presented by solid and dashed lines. It is evident that by increasing confining pressure and rubber content, more linear behaviour is observed. More importantly, damping ratio for a mixture with 25% rubber increased significantly. However, the effect of confining pressure for a mixture with 25% rubber is less pronounced. These results show the suitability of soil-rubber mixtures in reducing inertia force generated during earthquakes on infrastructure owing to the fact that damping ratio increases.

2.2 Soil-rubber mixture: leachate characteristics

The introduction of new or alternative (recycled waste) materials in building foundations may have benefits in terms of cost reductions and increased seismic resilience of low-rise buildings. However, it is essential to ensure that such innovations do not result in long-term negative impacts on the environment e.g. through the leaching of toxic chemicals into the surrounding soil environment, groundwater and surface water.

While tyre rubber itself, which makes up 75-80% of the weight of car and truck tyres (Basel Convention Working Group 1999), can be considered inert under ambient foundation conditions (Ministry for the Environment 2015), tyres contain ~ 1.5% by weight of hazardous compounds. Additives used in the manufacture of tyres are potentially harmful to the environment (e.g. organohalogen compounds, acidic solutions) and the steel fibres within the tyres can leach heavy metals (e.g. zinc, manganese, lead, cadmium) (Basel Convention Working Group 1999). A review of the leachate characteristics of tyres (MWH 2004) showed that, depending on if the steel components of the tyres are exposed, there may be elevated manganese and iron levels within the leachate and in groundwater (although at levels below relevant environmental standards). Levels of aluminium, zinc and organic compounds may be elevated in groundwater; however, the majority of the studies reported negligible levels. While these results were based on field and laboratory investigations, the risk of groundwater and soil contamination through tyre leachate is related to a number of different factors (tyre size, amount of exposed steel, distance to groundwater, permeability and chemistry of the soil, contact time with water, vertical water flow through soil, horizontal groundwater flow, leachate control systems (MWH 2004)) and these results cannot be directly related to specific sites. As far as the research team is aware of, no previous test results are available from the literature on the leaching properties of tyre rubber mixed with gravelly soils. These issues will be assessed in this study.

2.3 Rubberised concrete

The partial substitution of natural aggregates in concrete with recycled rubber particles has become an area of increased international interest over the past two decades. Research thus far has shown that the introduction of rubber particles can have significant impacts on the mechanical properties and dynamic characteristics of structural concrete. To effectively implement this novel, composite material within structural load-bearing members, a thorough understanding of its local and global behaviour is imperative.

The effect of incorporating rubber particles on the compressive strength, splitting tensile strength and elastic modulus of concrete has been well-documented, revealing significant reductions with increasing rubber replacement of course or fine aggregate (Najim & Hall 2010, Bompa et al 2017, Raffoul et al 2016). Xue & Shinozuka (2013) performed compressive tests on 27 standard cylinders with crumb rubber replacement ratios varying between 5- 20% course aggregate volume.

Reffoul et al (2017) investigated the effect of large rubber replacement ratios on compressive behaviour of concrete cylinders. Replacing 60% of course and fine aggregates with crumb rubber resulted in a decrease in compressive strength from ~ 62 MPa to 7 MPa. Despite this, the use of external confinement in the form of Aramid Fibre-Reinforced Polymer wraps restrained the excessive lateral expansion of the concrete, allowing the cylinders to reach over 70 MPa whilst achieving ultimate axial strains of up to 5% - fourteen times more than the conventional concrete cylinder.

Despite some reductions in mechanical properties, the inclusion of recycled rubber particles can result in significant enhancements in deformability and dynamic performance when compared to conventional concrete. Noaman et al (2016) proved the potential of crumb rubber to change the post-peak behaviour of concrete from brittle to ductile, as shown by the stress-strain behaviour presented in Figure 3. The results also displayed the increased strain capacity, flexibility and levels of energy absorption that were achievable.

Youssf et al (2015) investigated the seismic performance of a reinforced concrete column incorporating crumb rubber at 20% of sand volume. Despite a significant loss of compressive strength, the column sustained a lateral load of approximately 98% of the conventional column, all whilst dissipating 2.5 times more energy up

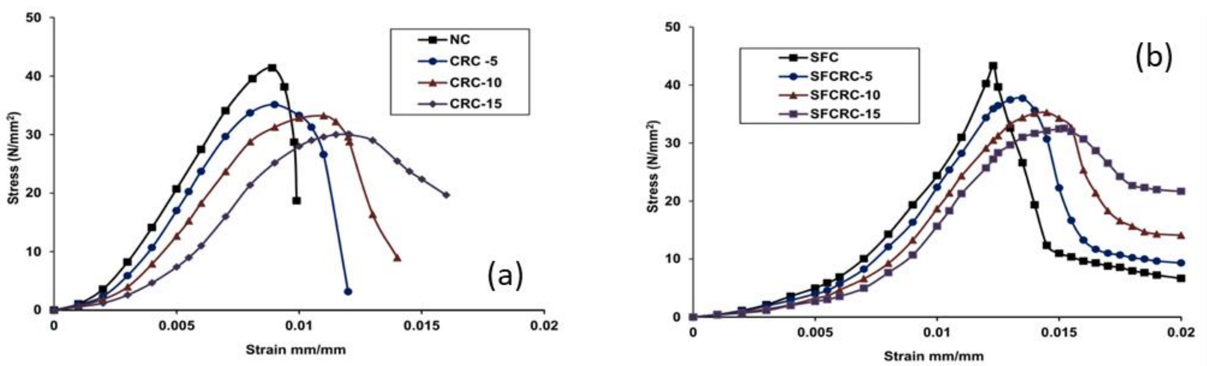

Figure 3: (a) Enhancement in deformability of concrete due to the inclusion of crumb rubber only; and (b) crumb rubber and steel fibres (adopted from Noaman et al 2016).

until a drift ratio of 4%. It was observed that the higher ductility of the rubberised concrete mix delayed concrete spalling and minimised the spreading of cracks, as shown in Figure 4. Xue & Shinozuka (2013) investigated the damping and seismic response of small-scale concrete columns with crumb rubber replacing 15% total aggregate volume. Free vibration tests resulted in an average damping ratio of 4.75% and 7.70% for conventional and rubberised concrete, respectively. This 62% increase indicates the energy dissipation capability of rubberised concrete and is attributed to the hyper-elastic nature of rubber, along with its high tensile strength and Poisson ratio. Seismic shake table testing showed that, on average, adding crumb rubber to concrete reduced the seismic response acceleration by ~ 27%. Such a decrease in acceleration results in less seismic forces being transferred to the rubberised concrete column – a desirable attribute for concrete structures in seismic environments.

2.4 Steel fibre-reinforced rubberised concrete

As discussed, the development of rubberised concrete can come at a cost to the mechanical properties of the material due to the softer response of rubber aggregates and the poor development of bond at the interfacial transition zone. A novel and effective method of limiting these reductions is the inclusion of small steel fibres. These fibres act as micro reinforcing within the concrete, "bridging" over micro tensile cracks and resisting the propagation of cracking within the interfacial transition zone. The introduction of these fibres to rubberised concrete has positive impacts on the compressive and splitting tensile strengths, along with further increases in toughness, ductility and energy absorption. Naoman et al (2016) found that the addition of steel fibres to rubberised concrete increased the 28-day and 56-day compressive strengths by 15 and 17%, respectively (see Figure 4at). The average increase in the splitting tensile strength was 34%; however, only a very small impact on the modulus of elasticity was recorded.

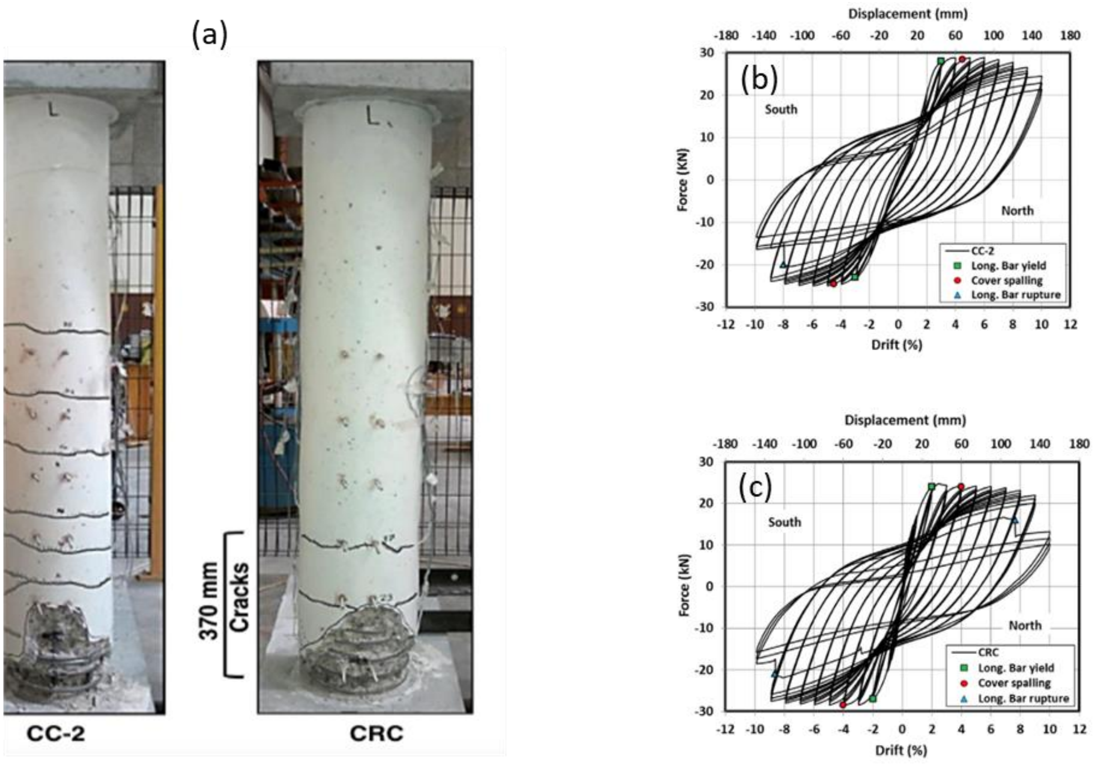

Figure 4: (a) Post-failure propagation of cracks; (b) hysteretic behaviour of conventional reinforced concrete; and (c) rubberised concrete (fromYoussf et al 2015).

Li &Li (2017) studied the effects of steel fibre and rubber particles on the flexural and seismic behaviour of concrete by conducting four-point bending tests on un-reinforced beams. A 36% increase in flexural strength and a deflection at failure of over three times that of conventional concrete was observed and attributed to the bridging effect of fibres in the post-cracking stage. Seismic behaviour was investigated via low-cycle lateral loading of a reinforced concrete column. Despite withstanding a lower peak load, the columns incorporating steel fibres and rubber particles failed at a peak displacement 45% higher than the conventional column, resulting in a significant increase in ductility factor. The energy dissipation also increased by 67%.

To date, a vast range of research has been undertaken on the utilisation of steel fibres in structural concrete. The accumulation of such work has led to the successful implementation of steel fibre-reinforced concrete in various applications throughout the world including architectural panels, pavements, slabs on grade and concrete shells. The enhanced toughness, ductility and flexural strength of the composite material has led to these high-performing concrete elements requiring only little or no steel reinforcement (Li & Li 2017).

Therefore, observations from state-of-the-art literature suggests, that the combination of fibres with rubber can become a viable alternative for low reinforcement ratio members such as foundation beams and raft. Moreover, the increased flexibility of the material results in a resilient solution against differential settlements induced by liquefaction and/or lateral spreading. The enhanced damping and energy dissipation will lead to reduced earthquake demands, whilst the increased ductility and deformability will decrease the extent of concrete cracking and delay the brittle failure of the concrete. The resulting solution, mainly envisaged for the residential market (medium density low-rise) is likely to enhance the overall seismic performance and therefore become a cost-effective alternative to current practice.

3 THE "ECO-RUBBER SEISMIC-ISOLATION FOUNDATION SYSTEMS" PROJECT

Seismic isolation (SI) with energy dissipation has the ability to significantly improve the seismic performance of buildings and structures. Historically, SI has been applied to buildings with special functional requirements and bridges. Nevertheless, its application to create new earthquake-resilient residential housing is feasible and would be of great significance in New Zealand.

On the other hand, waste tyres production and management are posing great environmental problems in New Zealand. However, waste tyres are a great source of environmentally-friendly and sustainable building materials. For example, they may provide novel and effective engineering solutions to attain structures with enhanced seismic resilience (Tsang 2008, 2012). This makes them ideal materials for developing affordable, medium-density, low-rise buildings that are in high demand in New Zealand.

To investigate if it is possible to develop a cost-effective "earthquake proof" engineered foundation-soil system for low-to-medium-density low-rise residential housing composed of a) shallow and resilient layer of mixed shredded tyres and gravel, and b) flexible rubber-concrete raft foundation (Figure 5), a multi-stage comprehensive geo-environmental-structural experimental research programme, funded by the MBIE Smart Idea research programme is being currently carried out at the University of Canterbury.

In this project five primary methodologies are used:

i. Geotechnical laboratory investigations to understand i) the macro-mechanical properties (i.e. shear strength, dynamic response, compressibility and permeability) of various rubber-gravel mixtures prepared at different densities and subjected to different levels of confining stress, and ii) the friction at the soil-foundation interface;
ii. Structural laboratory tests to identify the mechanical characteristics (e.g. cracking strength, damping etc.) of rubber-concrete for different mix designs i.e. percentage/dimensions of tyre shreds in the compound. This includes the effects of steel wires on the crack control;

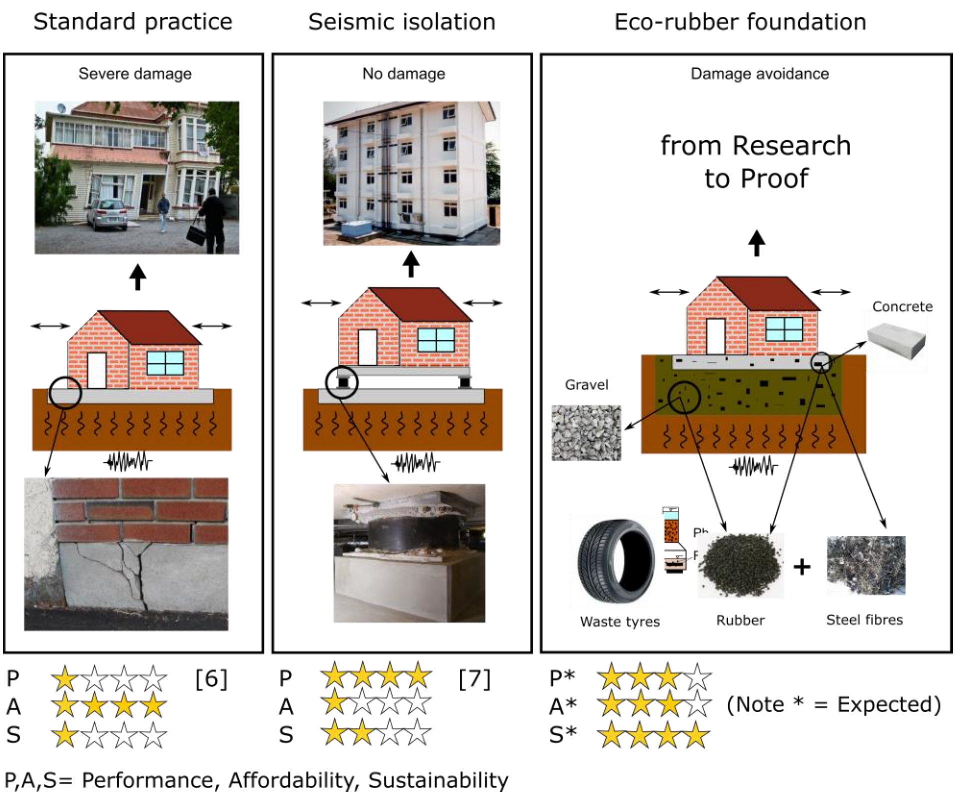

Figure 5: Performance, affordability and sustainability of traditional foundation and SI systems, and the proposed "Eco-rubber" SI foundation system.

iii. Environmental laboratory tests to identify and quantify the degradation profile of the shredded rubber, and the potential for soil/groundwater contamination including dispersion of contaminants (if any) on surrounding environments from the use of the proposed gravel-rubber mix. This data will then be used to assess the environmental impact and identify suitable countermeasures against contamination e.g. use of a reactive geomembrane to remove contaminants that would pollute the groundwater;

iv. Numerical models. Finite element methods (e.g. Abaqus and Plaxis) incorporating key information from (i) and (ii) to optimise the proposed foundation system (i.e. rubber-gravel mixture thickness; thickness of rubber-concrete foundation structure; possible use of alternate layers of rubber-gravel and rubber-concrete). Discrete element method (i.e. PFC3D to supplement (i) and provide insights on the micro-mechanical (grain size level) shear and compressible behaviour of gravel-rubber mixture and their interaction under external applied loads;

v. Proof-of-concept testing of the physical model of the ideal foundation system (obtained from iv) i.e. reduction of accelerations on the superstructure and no damage of structural elements in the superstructure.

4 CONCLUSIONS

In this paper, an innovative and cost-effective seismic isolation foundation system suitable for medium-density low-rise buildings is proposed. It consists of a dissipative filter made of granulated tyre rubber–gravel mixtures and fibre-reinforced rubberised concrete foundation structural elements. While this system is conceptually similar to conventional discrete elastomeric seismic isolation on rubber bearings (i.e. base-isolation), it differs in that the proposed system will be continuously distributed along the contact surface separating the building or series of multi-storey/multi-dwelling complexes from the ground. For this reason, the accelerations and consequent seismic inertial forces should be reduced by at least 40%.

5 AKNOWLWEGMENTS

The authors are grateful for the research support provided by the Ministry of Business, Innovation and Employment of NZ (MBIE Smart Ideas Re-search Grant No. 56289).

6 REFERENCES

Basel Convention Working Group. 1999. Technical Guidelines on the Identification and Management of Used Tyres, *Basel Convention on the control of transboundary movements of hazardous wastes and their disposal*, Document No. 10.

Bompa, D.V., Elghazouli, A.Y., Xu, B., Stafford, P.J. & Ruiz-Teran, A.M. 2017. Experimental assessment and constitutive of rubberised concrete materials, *Construction and Building Materials*, Vol 137, 246-260.

Brunet, S., de la Llera, J.C. & Kausel, E. (2016). Non-linear modeling of seismic isolation systems made of recycled tire-rubber, *Soil Dynamics and Earthquake Engineering*, Vol 85, 134-145.

Edinçliler, A. & Cagatay, A. (2013). Weak subgrade improvement with rubber fibre inclusions, *Geosynthetics International*, Vol 20(1), 39-46.

Lee, C., et al. (2014). Behavior of sand–rubber particle mixtures: experimental observations and numerical simulations, *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol 38(16), 1651-1663.

Li, Y. & Li, Y. 2017. Experimental study on performance of rubber particle and steel fibre composite toughening concrete,*Construction and Building Materials*, Vol 146, 267-275.

Mashiri, M.S., Vinod, J S. & Sheikh, M.N (2016). Liquefaction potential and dynamic properties of sand-tyre chip (STCh) mixtures, *Geotechnical Testing Journal*, 39(1): 69-79.

Ministry for the Environment. 2015. *Waste tyres economic research*, Report 3, May 2015, pp. 87.

MWH. 2004. *End-of-life tyre management: Storage options*, Final report for the Ministry for the Environment.

Najim, K.B. & Hall, M.R. 2010. A review of the fresh/hardened properties and applications for plain-(PRC) and self-compacting rubberised concrete (SCRC)), *Construction and Building Materials*, Vol 24, 2043-2051.

Noaman, A.T., Aby Bakar, B. H. & Akil, H.M. 2016. Experimental investigation on compression toughness of rubberized steel fiber concrete, *Construction and Building Materials*, Vol 115, 163-170.

Raffoul, S., Garcia, R., Escolano-Margarit, D., Guadagnini, M., Hajirasouliha, I. & Pilakoutas, K. 2017. Behaviour of unconfined and FRP-confined rubberised concrete in axial compression, *Construction and Building Materials*, Vol 147, 388-397.

Raffoul, S., Garcia, R., Pilakoutas, K., Guadagnini, M. & Medina, N.F. 2016. Optimisation of rubberised concrete with high rubber concrete: An experimental investigation, *Construction and Building Materials*, Vol 124, 391-404.

Seed, H. B., et al. (1986). Moduli and Damping Factors for Dynamic Analyses of Cohesionless Soils. *Journal of Geotechnical Engineering*, 112(11), 1016-1032.

Senetakis, K., et al. (2012). Dynamic properties of dry sand/rubber (SRM) and gravel/rubber (GRM) mixtures in a wide range of shearing strain amplitudes." *Soil Dynamics and Earthquake Engineering*, 33(1), 38-53.

Tsang HH (2008). Seismic isolation by rubber-soil mixtures for developing countries, *Earthquake Engineering and Structural Dynamic*, Vol 37, 283-303.

Tsang, H.-H., et al. (2012). Seismic isolation for low-to-medium-rise buildings using granulated rubber–soil mixtures: numerical study, *Earthquake Engineering & Structural Dynamics*, Vol 41(14), 2009-2024.

Xue, J. & Shinozuka, M. 2013. Rubberized concrete: A green structural material with enhanced energy dissipation capability, *Construction and Building Materials*, Vol 42, 196-204.

Youssf, O., ElGawady, M. A. & Mills, J. E. 2015. Experimental investigation of crumb rubber concrete columns under seismic loading. *Structures*, 3, 13-27.